

IRRIGATION WATER EFFECTS ON INFILTRATION RATE IN THE NORTHERN GREAT PLAINS

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Supplemental irrigation is expanding in the Northern Great Plains. Limited access to water of suitable quality for sustained irrigation and uncertainty about the impact of the use of marginal water on the soil resource will limit adoption of this practice. The objectives of this study were to determine the effect of irrigation water quality and amount on the infiltration rate, Q , at 50, 100, and 150 mm tensions, (h), and to relate the change in Q to changes in soil salinity and sodicity caused by irrigation. Tension infiltrometers were used to determine Q for soils at two sites in central North Dakota. Each site had 18 nonweighing lysimeters supporting alfalfa (*Medicago sativa* L.) that had been irrigated at three levels of irrigation (1ET, 2ET, and 3ET) for at least 10 years with either good quality surface water [electrical conductivity (EC) 0.1 S m⁻¹, sodium adsorption ratio (SAR) 4] or poor quality simulated groundwater (EC 0.34 S m⁻¹, SAR 16). At the site having sandy soils, Q , averaged over irrigation levels, was greater [$Q(50) = 5.34 \mu\text{m s}^{-1}$, $Q(100) = 3.74 \mu\text{m s}^{-1}$, $Q(150) = 2.96 \mu\text{m s}^{-1}$] in soils irrigated with good quality water than in soils irrigated with poor quality water [$Q(50) = 3.06 \mu\text{m s}^{-1}$, $Q(100) = 2.31 \mu\text{m s}^{-1}$, $Q(150) = 2.01 \mu\text{m s}^{-1}$]. Level of irrigation had no effect. At the site having loam textured soils Q was lower under the two higher irrigation levels than under the 1ET level, likely the result of greater replacement of divalent cations with Na⁺ at the higher leaching rates. At this site Q , averaged over irrigation levels, were greater [$Q(50) = 3.08 \mu\text{m s}^{-1}$, $Q(100) = 2.55 \mu\text{m s}^{-1}$, $Q(150) = 2.02 \mu\text{m s}^{-1}$] in soils irrigated with good quality water than in soils irrigated with poor quality water [$K(50) = 2.05 \mu\text{m s}^{-1}$, $K(100) = 1.63 \mu\text{m s}^{-1}$, $K(150) = 1.28 \mu\text{m s}^{-1}$]. Reductions in Q were directly related to increases in soil SAR (e.g., at the 1ET level of irrigation, SAR = 3 in soil irrigated with good quality water and SAR = 6 in soil irrigated with poor quality water) resulting from irrigation. These results suggest that these sulfatic soils are sensitive to Na⁺-induced deterioration. Soil physical deterioration was apparent at SARs much lower than the SAR 13 used to describe soils as sodic. Soil water compatibility in these soils is critical for sustainable irrigation. (Soil Science 1998;163:853-858)

Key words: Tension infiltrometer, salinity, sodicity, glacial soils, North Dakota.

WATER is the factor that most limits crop production in the semiarid Northern

Great Plains. Supplemental irrigation is an economically viable practice (Leitch et al. 1991), and irrigation is expanding. As irrigation expands, concerns regarding irrigation water quality and the effect of irrigation on the soil resource have emerged. Surface water, especially water from the Missouri River system, is generally of high quality for irrigation, and few soil-water compatibility problems occur unless drainage is inadequate. This situation is similar to that in southern

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Received May 1, 1998; accepted Aug. 7, 1998.

Alberta, where 280,000 ha of land have been irrigated with surface water for more than 50 years with few problems (Chang et al. 1985). In contrast, groundwater quality in the Northern Great Plains is highly variable and is often unsuitable for irrigation.

Because irrigation is profitable and adds stability to the production system, producers are showing increasing interest in this practice. Unfortunately, many producers do not have access to surface water and must rely on ground water. In the glaciated Northern Great Plains, soil and ground water anion chemistry is often dominated by SO_4^{2-} and HCO_3^- (Prunty et al. 1991). The compatibility of soil and irrigation water dominated by sulfatic salts was not well characterized in USDA Handbook 60 (United States Salinity Laboratory Staff 1954). In the Northern Great Plains, saline soils with sulfatic pore waters concentrate Na^+ during evaporation and freezing processes. The Ca^{+2} precipitates preferentially as gypsum and is removed in soils with electrical conductivity (EC) levels higher than 0.4 S m^{-1} (Timpson et al. 1986; Arndt and Richardson 1989). The Na^+ precipitates during cooling and freezing (Timpson et al. 1986; Beke and Palmer 1989; Richardson et al. 1990), keeping the Na^+ near the surface and moving the Mg^{+2} deeper. When the soils warm or thaw, the Na^+ solubilizes and concentrates in the pore water. This process may lead to the accumulation of more soluble Na^+ salts in near-surface horizons. Greenhouse experiments have demonstrated that irrigating with water similar to that of poor quality groundwater results in an increase in EC, sodium adsorption ratio (SAR), dispersion and migration of clay, and bulk density (Costa et al. 1991). These results, observations by other researchers, and comments by producers suggest that soil physical properties may deteriorate at lower SARs than predicted in USDA Handbook 60 (United States Salinity Laboratory Staff 1954).

Many glacially derived soils in the Northern Great Plains are considered nonirrigable when a fine-textured subsoil is present because of uncertainty about internal drainage capacity. A study was initiated in 1984 to measure the internal drainage capacity and to determine the irrigation potential of several representative glacially derived soils using nonweighing lysimeters. Included in the study was an assessment of the effect of irrigation amount and quality on alfalfa yield and soil properties. Results of this research have shown that these soils have sufficient inter-

nal drainage capacity to support irrigation (Doering et al. 1986; Trooijen and Reichman 1990); that alfalfa yields are not affected by irrigation amount and quality (unpublished data); and that soil salinity and sodicity increased, and the magnitude of that increase was related to the EC and SAR of the water applied (Wienhold and Trooijen 1995). Little is known about how these changes in EC and SAR affect the physical properties of these soils or about the implications for long-term irrigation of these soils. The objective of the present study was to determine if irrigation water amount and quality affected infiltration rate (Q) in these soils.

MATERIALS AND METHODS

The effect of irrigation water quality on Q was measured at two sites; the Menoken township site (T139N, R78W, Sec. 19, SE 1/4) and the Naughton township site (T140N, R79W, Sec. 35, SW 1/4). These sites are located in central North Dakota, 20 km east of Bismarck in Burleigh county. Soils at the Menoken site are Lihen sandy loam (sandy mixed Entic Haploborolls), Roseglen loam (fine-loamy, mixed Pachic Haploborolls), and Parshall sandy loam (coarse loamy, mixed Pachic Haploborolls). These soils developed on aeolian-lacustrine sediments deposited over fine lacustrine sediments. Soils at the Naughton site are Falkirk loam (Fine-loamy, mixed Pachic Haploborolls) and Bowbells loam (Fine-loamy, mixed Pachic Argiborolls). These soils developed on slope-worked alluvium deposited on till. Soils at both sites have moderately fine textured layers classified as slowly permeable within 1.8 m of the surface and are well drained.

Alfalfa has been grown at the Menoken Site since 1984 and at the Naughton Site since 1986. Each site had alfalfa planted in 18 nonweighing lysimeters ($2.5 \text{ m} \times 2.5 \text{ m}$ square $\times 2.3 \text{ m}$ deep) that contained undisturbed soil that had retained the natural drainage characteristics of the soil profile. The original objective of the study was to determine if the internal drainage capacity of these soils having fine-textured subsoils, was capable of supporting irrigation (Doering et al. 1986; Trooijen and Reichman 1990). To test the internal drainage capacity, three irrigation water levels were applied. Irrigation was applied so that precipitation plus irrigation would be one (1ET), two (2ET), or three (3ET) times the calculated Jensen-Haise alfalfa evapotranspiration (Jensen et al. 1970), with weekly adjustments similar to a crop coefficient from Lundstrom and Stegman (1983).

Two irrigation water qualities were applied. Water from the Heart River, a tributary of the Missouri River, had an EC of 0.1 S m^{-1} and a SAR of 4. Water similar to some shallow groundwater in North Dakota with an EC of 0.34 S m^{-1} and a SAR of 16 was produced by adding NaCl and CaCl_2 (ratio of 6:1 by weight) to the Heart River water. Water was applied by flood irrigation. The experiment was replicated three times, with treatments assigned to the lysimeters in a randomized complete block design. Soil cores to a depth of 1.5 m were collected periodically during the study and sectioned into six increments (0–0.15, 0.15–0.3, 0.3–0.6, 0.6–0.9, 0.9–1.2, and 1.2–1.5 m). A saturated paste extract was obtained for each soil sample and the EC (Rhoades 1982) and SAR (U.S. Salinity Laboratory Staff 1954) determined.

The infiltration rate was measured using a tension infiltrometer (Vadose Zone Equipment Co., Amarillo, TX 79106)⁴ similar in design to that described by Perroux and White (1988). The wetting area of the infiltrometer was 0.03 m^2 . The infiltrometer was automated with transducers (Ankeny et al. 1988), and data were recorded with an electronic datalogger (Campbell Scientific, Inc., Logan UT, 84321)⁴.

The infiltration rate was measured in each of the 18 lysimeters at both sites. Alfalfa was clipped at the soil surface, and 4 mm of fine silica sand was placed on the soil to provide good contact between the tension infiltrometer and the soil. The infiltration rate was measured at tensions of 50, 100, and 150 mm. The infiltration rate was measured at the lowest tension and then sequentially at higher tensions. Infiltration at each tension was measured for 30 min, with reservoir level readings taken every 15 s. Preliminary studies at these sites suggested that steady state infiltration rates were achieved within 20 min, resulting in a high correlation between cumulative infiltration and time during the last 10 min of each run. Infiltration rate was compared among irrigation and salinity treatments using ANOVA, with differences declared significant at the 0.05 probability level.

RESULTS AND DISCUSSION

As reported previously (Wienhold and Trooien 1995), 10 years of irrigation changed the soil EC and SAR in the 0-to 0.15-m depth. The magnitude of the change in soil EC and SAR differed between the two sites, likely because of

textural differences in the soils at these sites. In addition, changes in salinity and sodicity were a function of the quality and quantity of irrigation water applied. Because the salinity and sodicity status of these soils will be used to explain the observed response of infiltration rates to the irrigation treatments, results from the previous study will be summarized here.

At the Menoken site, soil EC had equilibrated with that of the irrigation water for both water sources and was similar among the levels of irrigation. Soil SAR in plots irrigated with Heart River water equilibrated with that of the irrigation water in plots receiving 1ET of irrigation (soil SAR = 4) and increased slightly (soil SAR = 6) as irrigation amount increased to 2ET or 3ET. Soil SAR in plots irrigated with simulated groundwater was 10 and increased slightly, to 14, as the amount of irrigation increased from 1ET to 3ET. Soils at the Menoken site are coarse textured, and salt inputs affected soil salinity and sodicity readily. When these soils are irrigated, the low clay content provides them with little buffering capacity, and relatively low salt inputs result in rapid changes in salinity and sodicity.

At the Naughton site, soil EC was similar to that of the irrigation water in plots receiving Heart River water and was similar across levels of irrigation. Soil SAR in plots receiving Heart River water at the 1ET level was slightly lower (soil SAR = 3) than that of the irrigation water and increased (soil SAR = 5) at the two higher rates of irrigation. Soil EC for plots irrigated with simulated groundwater increased from 0.08 S m^{-1} in the 1ET treatment to 0.18 S m^{-1} in the 2ET and 3ET treatments. Soil in plots receiving simulated groundwater at the 1ET level of irrigation had a SAR of 6. Soil SAR increased (soil SAR = 11) as the amount of simulated groundwater used for irrigation increased to 2ET or 3ET. Soils at the Naughton site are finer textured than those at the Menoken site. Larger salt inputs are required to change the salinity and sodicity status of these finer textured soils. As irrigation continues, soil EC and SAR will likely continue to increase. Deterioration of these soils as a result of salinity and sodicity will be harder to ameliorate because of the larger amounts of salt retained by the soil.

At the Menoken site, values for Q were not affected by level of irrigation water applied, and the interaction between level of irrigation water and water source was not significant. Therefore, Q results for the Menoken site are averaged over irrigation levels and presented as a

⁴Mention of trade names or proprietary products does not indicate endorsement by USDA and does not imply its approval to the exclusion of other products that may be suitable.

TABLE 1
Infiltration rate (mean \pm SEM) as a function
of water source at the Menoken site

Tension	Water source	
	Heart River	Simulated ground water
mm	$\mu\text{m s}^{-1}$	
50	5.339 \pm 0.685 a†	3.056 \pm 0.293 b
100	3.745 \pm 0.405 a	2.309 \pm 0.233 b
150	2.961 \pm 0.382 a	2.012 \pm 0.230 a

†Values in a row followed by the same letter are not significantly different at $P = 0.05$.

function of water quality (Table 1). Variation in $Q(150)$ resulted in a statistically insignificant difference ($P = 0.07$) for soils irrigated with the two water qualities, whereas $Q(100)$ and $Q(50)$ were lower in soils irrigated with simulated groundwater than in soils irrigated with Heart River water. The trend for reduced water movement at $Q(150)$ and reduced water movement at the other two tensions suggests that soil structure has been degraded as sodicity has increased at this site.

At the Naughton site, values for Q were affected by level of irrigation and water quality, but the interaction between level of irrigation and water quality was not significant. Infiltration rates averaged across water qualities and presented as a function of level of irrigation demonstrate that Q declined with increasing level of irrigation, but because of high variation, the decline at $Q(150)$ was not statistically significant (Table 2). $Q(100)$ and $Q(50)$ were lower in soil receiving the 2ET and 3ET levels of irrigation than in soil irrigated at the 1ET level. Higher levels of irrigation resulted in greater leaching and replacement of exchangeable cations with Na^+ and, as noted above, sodicity increased as the amount of irrigation increased. The deterioration in soil structure resulting from the increase in sodicity reduced Q .

Infiltration rate averaged across irrigation levels and presented as a function of water quality demonstrated that irrigation with simulated groundwater reduced Q at all tensions when compared with irrigation of soils with Heart River water, but as with soils at the Menoken site, high variation in $Q(150)$ resulted in a nonsignificant difference ($P = 0.08$; Table 3). Applying poor quality groundwater added salt to the soil and, as noted above, increased sodicity, which resulted in a deterioration in soil structure that reduced Q . As noted above, continued irrigation of these soils will likely result in a further increase in salinity and sodicity, and soil structure will likely continue to deteriorate under these conditions.

The observed reduction in Q suggests that there has been a deterioration in soil structure at both sites. There are two mechanisms by which soil structure can be reduced: (i) dispersion of clay, followed by blocking of water-conducting pores by lodged clay particles (Frenkel et al. 1978) and (ii) swelling of clays, resulting in a reduction in pore size. Dispersion occurs when the soil solute concentration is below a threshold level for a given sodicity level, and swelling occurs at high sodicity and high soil solute concentrations (Pupisky and Shainberg 1979). Using curves generated by Curtin et al. (1994) relating sodicity to swelling for several glacially derived soils in southern Saskatchewan, swelling appears to be a minor contributor to the reduction in Q observed in our study. More likely, dilution of the soil solution by precipitation has reduced the solute concentration below the dispersion threshold, and lodging of clay particles in conducting pores has resulted in a reduction in Q in these soils.

Threshold concentration curves (Quirk and Scholfield 1955) have been used to describe the relationship between hydraulic conductivity and soil solution concentration. Curtin et al. (1994) developed threshold concentration curves for a number of glacially derived soils from southern

TABLE 2
Infiltration rate (mean \pm SEM) as a function of level of irrigation at the Naughton site

Tension	Level of irrigation		
	1 ET	2 ET	3 ET
mm	$\mu\text{m s}^{-1}$		
50	3.141 \pm 0.386 a†	2.170 \pm 0.131 b	2.255 \pm 0.369 b
100	2.655 \pm 0.333 a	1.828 \pm 0.150 b	1.626 \pm 0.263 b
150	2.015 \pm 0.332 a	1.509 \pm 0.153 a	1.307 \pm 0.351 a

†Values in a row followed by the same letter are not significantly different at $P = 0.05$.

TABLE 3
Infiltration rate (mean \pm SEM) as a function
of water source at the Naughton site

Tension mm	Water source	
	Heart River	Simulated ground water
	$\mu\text{m s}^{-1}$	
50	3.084 ± 0.276 a [†]	2.053 ± 0.205 b
100	2.548 ± 0.258 a	1.627 ± 0.159 b
150	2.020 ± 0.240 a	1.280 ± 0.204 a

[†]Values in a row followed by the same letter are not significantly different at $P = 0.05$.

Saskatchewan. Although each soil has its own characteristic curve, threshold concentration values were found to increase as soil clay content increased (Curtin et al. 1994); this means that as clay content increased, higher solute concentrations were needed to prevent unstable conditions. This relationship suggests that finer textured soils are more susceptible to structural deterioration than are sandy soils. Our results support those of Curtin et al. (1994) in that the change in Q of loam soils at the Naughton site was similar in magnitude (reduced 33 to 37%) to that of the sandy soils at the Menoken site (reduced 32 to 43%) even though changes in salinity and sodicity at the Naughton site were less than those at the Menoken site. In addition, soil structure will continue to deteriorate at Naughton because soil EC and SAR will likely continue to increase until an equilibrium between the salinity and sodicity of the soil and the irrigation water has been established.

Current terminology classifies a soil as sodic at an SAR of 13 (Soil Science Society of America 1997). At the Naughton site, Q in soil with a SAR of 6 was nearly half that of soil having a SAR of 3, suggesting that physical conditions deteriorated at much lower SARs than those considered sodic. While sodicity of the soils irrigated with ground water at the Naughton site are well below the SAR of 13 needed to classify them as sodic (Soil Science Society of America 1997), they are exhibiting physical characteristics that are problematic for continued irrigation.

CONCLUSIONS

This study shows that irrigation water quality has the potential to affect physical properties of these glacially derived sulfatic soils significantly. The results suggest that careful water management is needed for these finer-textured

soils to ensure that soil physical properties do not deteriorate under irrigation. These sulfatic soils appear more susceptible to Na^+ -induced deterioration than chloridic soils, and irrigation water quality recommendations developed for chloridic soils may not be appropriate for these glacially derived soils. Producers wishing to incorporate irrigation of these soils into their production system will need access to a good quality water source.

ACKNOWLEDGMENTS

The authors thank John Bullinger and Wallace Sellner for maintaining the field sites, Ivana Witt for collecting the tension infiltrometer data, and the Burleigh County Water Resources District for supplying equipment and access to the sites.

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